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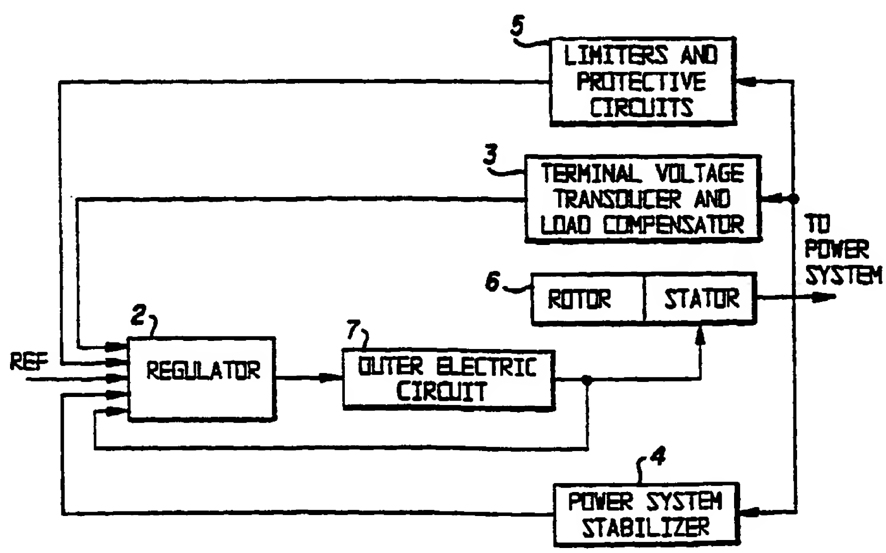

(57) Abstract

A rotating electric machine for direct connection to high-voltage networks, in which the magnetic circuit adapted for high voltage comprises a permanent magnetic rotor, stator and main and auxiliary flux control windings in operative relation. At least one of the windings is a conductor surrounded by a magnetically permeable, field confining insulation system.

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A METHOD AND DEVICE FOR CONTROLLING THE MAGNETIC FLUX IN A ROTATING HIGH VOLTAGE ELECTRIC ALTERNATING CURRENT MACHINE WITH PERMANENT MAGNET ROTOR

BACKGROUND OF THE INVENTION

The present invention relates to a method and device for controlling the magnetic flux in a rotating high voltage electric alternating current machine with a permanent magnet rotor and at least one auxiliary winding in the stator.

The invention relates mainly to electric alternating current machine intended to be directly connected to a distribution or transmission network comprising a magnetic circuit with a magnetic core, a main winding, at least one auxiliary winding, and a permanent magnet rotor. Such electric machines comprise synchronous machines which mainly are used as generators for connection to distribution and transmission networks, commonly referred to below as power networks. The synchronous machines are also used as motors and synchronous compensators. The technical field also comprises outer pole machines and synchronous flux machines.

The rotor of a synchronous machine usually consists of electromagnets or permanent magnets that under steady state conditions rotates with a speed that is proportional to the frequency of the current in its stator winding which usually is a three phase winding. The stator is essentially the same with both types of rotors.

If the rotor consists of electromagnets the field winding is usually feed with dc power from either a static or a rotating exciter. By controlling the dc current in the field winding, the magnetic flux in the machine can be controlled and thus can e.g. the voltage at the stator

terminals be controlled. Various control functions are commonly included in the exciter control system such that the machine behaves in a way acceptable for the system. Examples of such control functions are AVR (Automatic Voltage Regulator) and PSS (Power System Stabilizer).

The following is a brief description of various subsystems encountered in a typical excitation control system as shown in Fig. 1.

Exciter 1 provides the dc power to the synchronous machine field winding, constituting the power stage of the excitation system.

Regulator 2 processes and amplifies input control signals to a level and form appropriate for control of the exciter.

Terminal voltage transducer 3 and load compensator 3 senses stator terminal voltage, rectifies and filters it to dc quantity, and compares it with a reference which represents a desired terminal voltage. In addition, load (or line-drop, or reactive) compensation may be provided, if it is desired to hold constant voltage at some point electrically remote from the generator terminal. Power System Stabilizer 4 provides an additional input signal to the regulator to damp power system oscillations. Some commonly used input signals are rotor speed deviation, accelerating power, and frequency deviation. Limiters and protective circuits 5 include a wide array of control and protective functions which ensures that the capability limits of the exciter and the synchronous machine are not exceeded. Some of the commonly used functions are the field-current limiter, maximum excitation limiter, terminal voltage limiter, volts-per-Hertz regulator and protection, and underexcitation limiter.

Synchronous machine 6 has a rotor and a stator. The magnetic flux in the machine is controlled via the exciter 1 and the field winding of the rotor.

If the rotor consists of permanent magnets there is no need for a source of direct current for excitation. Consequently, one important advantage with permanent magnets in the rotor is that there are no excitation losses. This drastically reduces the need for cooling of the rotor. The result is a more efficient machine. It also gives possibilities for a more compact rotor design.

The main disadvantage with a permanent magnet rotor is that field control is not practical. The operating characteristics of permanent magnet machines, both generators and motors, are consequently constrained by the lack of ability to adjust the field. As a free-standing generator, the terminal voltage will vary with the load. To keep this voltage within reasonable limits, it may be necessary sometimes to control the load power factor by use of adjustable shunt capacitors connected to the power network in the vicinity of the generator. As a motor, the permanent magnet machine is most widely used as a variable-speed drive supplied by a source of controllable voltage and frequency.

There are a number of different permanent magnet rotor designs. Some of them can be found in Chapter 9 in the book *Handbook of Electric Machines* by S.A. Nasar, McGraw Hill, 1987.

SUMMARY OF THE INVENTION

The invention comprises an electric machine of the type described in the above-mentioned co-pending applications and which employs a winding in the form of a cable, a stator, a rotor comprising permanent magnets and at least one main winding and at least one auxiliary winding. The main winding is connected to the power network by producing or consuming active and reactive power.

According to the invention it is possible to control the magnetic flux in the machine

although the rotor has permanent magnets. In the invention, where one main winding and one auxiliary winding is encased in the stator, this is achieved by connecting an outer or external electric circuit to the auxiliary winding. The outer electric circuit is controlled such that a suitable current flows in the auxiliary winding(s), thus influencing the magnetic flux. It is in this way possible to replace all relevant control functions typically found in a conventional control system working through the field winding in a machine with electromagnets in the rotor. Furthermore, it is possible to add some control functions which are not possible to implement when working through a field winding. Such functions can be dynamic breaking to reduce rotor acceleration, controlling the magnetic flux in order to reduce the fault current and reduce the generated harmonics in the machine.

The following is a brief description of various subsystems for a synchronous machine according to the invention as shown in Fig. 2 where similar elements have the same reference numerals.

Unlike the exciter 1 in Fig. 1, which controls the rotor, the outer electric circuit 7 controls the current in the auxiliary winding such that the required influence of the magnetic flux is achieved.

Regulator 2 processes and amplifies input control signals to a level and form appropriate for control of the outer electric circuit.

Terminal voltage transducer and load compensator 3 senses stator terminal voltage, rectifies and filters it to dc quantity, and compares it with a reference which represents a desired terminal voltage. In addition, load (or line-drop, or reactive) compensation may be provided, if it is desired to hold constant voltage at some point electrically remote from the generator terminal.

Power System Stabilizer 4 provides an additional input signal to the regulator to damp power system oscillations. Some commonly used input signals are rotor speed deviation, accelerating power, and frequency deviation.

Limiters and protective circuits 5 include a wide array of control and protective functions which ensures that the capability limits of the outer electric circuit and the synchronous machine are not exceeded. Some of the functions are main winding terminal voltage limiter, auxiliary winding terminal voltage limiter, stator main winding current limiter, stator auxiliary winding current limiter and volts-per-Hertz regulator.

Synchronous machine 6 according to the invention has at least one auxiliary winding and a permanent magnet rotor.

As mentioned above, if the air gap flux is controlled from an auxiliary winding in the stator in a synchronous machine, other control objectives can be achieved than if the air gap flux only is controlled from the rotor. This is for instance the case if the auxiliary winding is a three-phase winding which can be controlled in an unsymmetrical way.

Furthermore, for a synchronous machine according to the invention, the time constants between the auxiliary winding and the air gap flux are smaller than the time constants between the field winding and the air gap flux for a machine with a rotor consisting of electromagnets. This implies that it is possible to affect the air gap flux faster according to the invention via the auxiliary winding than from the field winding for a machine with a rotor consisting of electromagnets.

With this invention the advantages of a permanent magnet rotor can be utilized, that is for example drastically lower rotor losses, simpler rotor cooling, possibility of a more compact rotor design as compared to a rotor consisting of electromagnets.

The additional losses in the stator, due to copper losses in the auxiliary winding, are far more easy to handle than the rotor losses in a rotor with electromagnets. This is a consequence of the fact that the stator is stationary.

Voltage regulation is with the invention achieved by controlling the outer electric circuit such that it injects or extracts reactive power from the auxiliary winding.

Fig. 3 illustrates some characteristic features of a capability diagram active power P versus Q reactive power for a machine according to the invention where: CL corresponds to the thermally based current limit for the main winding, MP corresponds to the maximum power of the turbine, C represents the capability without auxiliary winding, CI and CC corresponds to the thermally based current limit for the auxiliary winding (assuming that the auxiliary winding carries negligible amount of active power), the limit CI corresponds to a inductive current in the auxiliary winding whereas limit CC corresponds to an capacitive current, the shaded region NO corresponds to the region of normal operation. Point OP represents an operating point where the losses in the auxiliary winding are zero assuming that no active power is extracted or injected in the auxiliary winding. TLC is an operating point at the capacitive current limit CC. TLI is an operating point at the inductive current limit CI. In order to move between the operating point OP and TLC the amount of reactive power injected into the auxiliary winding is increased. In this example, both the main winding and the auxiliary winding is at there thermal limits at TLC. In order to move between OP and TLI the amount of reactive power extracted from the auxiliary winding is increased.

It is reasonable to compare the losses in the auxiliary winding for a machine according to the invention and the excitation losses for a machine with a rotor consisting of electromagnets. The latter has zero field current, and minimal excitation losses, in the under

excited region of the capability in the vicinity of UE, whereas a machine according to the invention has minimal losses in the auxiliary winding along curve C. Clearly, a synchronous machine frequently is operated at high turbine power in the vicinity of curve C, but seldom in the vicinity of UE. This shows that a machine according to the invention often may have an efficiency superior to a machine with rotor having electromagnets.

It is possible to equip the permanent magnet rotor with damping windings, it is also possible to exclude them.

Another advantage with this invention is of course the elimination of the problem of supplying a rotating winding with electric power, as is the case with a rotor with electromagnets

According to an exemplary implementation of the invention the auxiliary winding(s) described in the copending applications and herein operate at a relatively low voltage. The connected electric circuits therefore comprise inexpensive low voltage equipment, as compared to equipment connected to the main winding.

An example of where the auxiliary winding 56 can be placed in the stator (51) is shown in Fig. 4A. It is also possible to equip the permanent magnet rotor with an auxiliary winding with means to control the current in the winding. In other words, the auxiliary winding acts in this implementation as a field winding. The rotor becomes a hybrid between a permanent magnet rotor and an electromagnet rotor.

Voltage regulation of a machine according to the invention can be accomplished by injecting or extracting reactive power from the auxiliary winding 56.

A simple way to implement this would be according to Fig. 14, where a capacitor and a reactor has been attached to the auxiliary winding via breakers. By closing one of the

breakers reactive power is either produced by the capacitor and injected into the auxiliary winding or consumed and extracted from the auxiliary winding. As seen from the main winding, reactive power can in this way be produced or consumed by the machine.

In order to achieve a smother control, the capacitor and the reactor could be divided into several mechanically switched units, according to Fig. 15. Another way to achieve smother control would be by replacing the mechanically switched capacitor and reactor with a thyristor switched capacitor (TSC) and thyristor switched reactor (TSR), SVC (Static Var Compensator), according to Fig. 16. The amount of reactive power injected into or extracted from the auxiliary winding can in this way be continuously controlled.

If the purpose of the auxiliary winding also is to provide the station with auxiliary power, a preferred implementation involves an AC/DC DC/AC converter with an energy store (10) (*e.g.* batteries) connected to the DC bus bar according to Fig. 8. The converter (11) is used for controlling the voltage at the auxiliary voltage bus bar at all times and for delivering active power to the load connected to the auxiliary bus bar at rated frequency. In addition the converter (9) closest to the auxiliary winding can be controlled such that it can inject or extract reactive power from the auxiliary winding.

Other implementations are possible, *e.g.* according to Fig. 7 and Fig. 9. If the machine is equipped with two windings the implementation according to Fig. 11 can be used.

A characteristic feature of a power system tending towards voltage collapse is that synchronous generators in a region hits their limits for reactive power production, either by hitting the field current limit or the armature current limit, see *e.g.* Section 2.2.3 in CIGRÉ report "Criteria and Countermeasures for Voltage Collapse". In such an emergency situation the machines are usually allowed to pass these limits for a period of time, depending on the

time constants for heating of rotor and stator respectively.

With a stator design according to the invention, the time constants for stator heating are large as compared to the corresponding time constants for a conventional machine. This is mainly due to a preferred choice of insulation system (XLPE). With an auxiliary stator winding according to the invention, the additional reactive power is obtained by injecting reactive power into the auxiliary stator winding. The auxiliary stator winding may have the same insulation system as the main winding and it can thus be designed to have similar time constants for heating. The large time constants for heating of the stator can thus be fully utilized. A machine according to the invention can thus be overloaded for a longer period of time, as compared with a machine with rotor consisting of electromagnets, providing the operators of the power network with time to take actions to prevent voltage collapse.

The stator main winding current limiter and the stator auxiliary winding current limiter should be designed such that these time constants are fully utilized.

During a transient disturbance following a power network fault and clearing of the fault by isolating the faulted element, the generator terminal voltage is low. For a conventional generator, the automatic voltage regulator responds to this condition by increasing the field voltage which has a beneficial effect on transient stability. The effectiveness of this type of control depends on the ability of the excitation system to quickly increase the field voltage to the highest possible value.

With a machine according to the invention, the high speed excitation system working through the rotor circuit can be replaced with an electric circuit attached to the auxiliary winding which quickly can increase the voltage of the main winding. The electric circuit could consist of a TSC, as in Fig. 16. The input signal could be the same as for the

conventional high speed excitation system. The system working through the auxiliary winding has smaller time constants than the system working through the field circuit. Furthermore, the insulation system of the auxiliary winding can withstand a high balanced fundamental frequency over voltage, partly because it is dimensioned to withstand ground faults in the external circuit and partly because the XPLE insulation can withstand high fundamental frequency overvoltages for several minutes. This allows for a high ceiling voltage. In other words, the system working through the auxiliary winding can quickly affect the voltage of the main winding.

Dynamic braking uses the concept of applying an artificial electric load during a transient disturbance to increase the electrical power output of machines and thereby reduce rotor acceleration. One form of dynamic braking involves the switching in of shunt resistors for about 0.5 seconds following a fault to reduce the accelerating power of nearby machines and remove the kinetic energy gained during the fault. Bonneville Power Administration (BPA) has used such a scheme for enhancing transient stability for faults in the Pacific Northwest; the brake consists of a 1400 MW, 240 kV resistor.

With a machine according to the invention, active power could be extracted from the auxiliary winding in case of a disturbance in the network connected to the main winding. This would reduce the accelerating power and thus reduce the rotor acceleration. A preferred implementation would be to connect the resistance in shunt to the auxiliary winding via a breaker. With a breaker switched resistance, see Fig. 17, care should be taken to avoid instability on the "backswing" which may occur if the resistor remain connected too long. Other implementations are also possible, *e.g.* by utilizing a thyristor controlled resistor, see Fig. 18. Comparing this solution with *e.g.* the BPA installation, it can be noted that

according to a preferred implementation of the invention the voltage level is typically lower, implying simpler equipment, and that this equipment primarily is used to brake the machine not a large group of machines which may be the case if the brake is installed in the power network.

According to an advantageous implementation of the braking idea is to combine it with the fast voltage control described above, since both have a beneficial effect on transient stability.

Another application of the brake as described above is to use it as a brake for machines that are used for producing peak power, *i.e.* machines that need to start and stop often. When braking the machine the problem is to convert the energy stored as kinetic energy. There are essentially two ways to accomplish this, either by utilizing mechanical brakes or electrical brakes. Mechanical brakes have a rather short life time, *i.e.* they require frequent maintenance and repair. The simplest way to implement the electrical brake, after that the mechanical torque has been removed and the machine has been disconnected from the system, is by applying a short circuit to the terminals of the machine and magnetize the machine such that *e.g.* rated current is achieved in the stator winding. This current creates copper losses which gives a very good braking effect, in particular at lower speed.

With a machine according to the invention it is of course possible to implement an electrical brake by applying a short circuit to the main winding terminal. However, as this terminal is a high voltage terminal, the device with which the short circuit is accomplished needs to be designed for high voltage. In other words, it may become expensive. A preferred implementation is instead to accomplish the short circuit at the auxiliary winding terminals, preferrebly via a braking resistor as in Fig. 17, a thyristor controlled resistor as in Fig. 18, or

via loading an energy store as in Fig. 6.

Reduction of power oscillations in the power network.

There are a number of components in the power network which can be used to damp power oscillations. It is for instance possible to equip SVC and HVDC plants with supplementary control for this purpose. However, one of the most common ways to add damping to generator rotor oscillations is by controlling its excitation using auxiliary stabilizing signal(s). This control function is usually called a PSS (Power System Stabilizer). Fig. 19, from the book *Power System Stability and Control* by Prabha Kundur page 767, illustrates how a block diagram of a generator with voltage regulator and PSS may look like. To provide damping, the PSS must produce a component of electric torque in phase with the rotor speed deviations. A logical signal to use for controlling generator excitation is the rotor speed deviation. If the exciter transfer function $G_{ex}(S)$ and the generator transfer function between field voltage (ΔE_{fd}) and electric torque (ΔT_e) were pure gains, a direct feedback of deviation in rotor speed ($\Delta\omega_r$) would result in a damping torque component. However, in practice both the generator and the exciter (depending on its type) exhibit frequency dependent gain and phase characteristics. In the ideal case, with the phase characteristic of the PSS ($G_{PSS}(s)$) being an exact inverse of the exciter and generator phase characteristics to be compensated, the PSS would result in a pure damping torque at all oscillating frequencies. It is however difficult to design the PSS such that pure damping is obtained for all frequencies, partly because the phase characteristics changes with system conditions. Normally, the frequency range of interest is 0.1 to 2.0 Hz, and the phase-lead network should provide compensation over this range.

If the machine is equipped with an auxiliary winding according to the invention, the

conventional PSS, which works through the field winding, could be replaced by a PSS working through the auxiliary winding. Fig. 6 shows a schematic single line diagram of a preferred solution for this purpose. The converter (9) can be controlled such that power is injected into or extracted out from the auxiliary winding such that the power oscillation as seen as an oscillation in air gap torque is reduced or eliminated, thus damping the system oscillation. Other implementations such as, *e.g.* according to Fig. 8 are also possible. Input signals for this control loop could for instance be based on rotor speed or active power as seen from the main winding. It is easier to design a PSS working through the auxiliary winding such that more or less pure damping is obtained for a broad frequency range since the gain and phase is less frequency dependent between the auxiliary winding and the electric air gap torque.

Reduction of internal fault currents.

When a machine is connected to a power network without step up transformer both the power network and the machine, due to the rotating magnetic flux, will give a contribution to the fault current in the machine in case of an internal ground fault.

If an internal ground fault occurs in the machine it can result in a high fault current which may damage the machine. The damage of the machine depends on the magnitude and the duration of the fault current. To reduce the damage in the machine it is desirable to reduce both the magnitude and the duration of the fault current.

In a conventional generator plant this is achieved by disconnecting the machine from the power network as fast as possible and by controlling the field current such that it decreases as fast as possible in order to remove the rotating magnetic flux in the machine.

With a machine with a permanent magnet rotor and with a conventional design of the

stator it is not possible to reduce the rotating magnetic flux in the machine. This is due to the constant magnetic flux from the permanent magnets.

With a machine according to the invention with an auxiliary winding in the stator it is possible to reduce or cancel the rotating magnetic flux in a machine with a permanent magnet rotor and thus reduce the contribution of the fault current. This can be accomplished by injecting a current in the auxiliary winding which is controlled in such way that it produces a rotating magnetic flux in the machine that will superimpose on the rotating magnetic flux produced by the permanent magnet rotor such that the resulting magnetic flux is reduced or cancelled. This will reduce the fault current magnitude and duration.

The invention can for instance be realized, as shown in Fig. 12, by connecting the auxiliary winding (4) to a frequency converter (15) that can generate a controllable current in the auxiliary winding (4). If an internal ground fault occurs in the machine (1) the machine (1) is disconnected from the power network (7) with the breaker (3). Furthermore, the frequency converter (15) injects a current in the auxiliary winding (4) such that a rotating magnetic flux is produced that will superimpose on the rotating magnetic flux produced by the permanent magnet rotor such that the resulting magnetic flux is reduced or cancelled.

In Fig. 12 the frequency converter (15) is controlled by the measurement equipment (19), measuring the rotor angle with the rotor angle measurement signal (24), via control signals (20).

A fast elimination of the magnetic flux by controlling the field current is complicated due to the relatively large time constant for the field winding and due to the difficulties to transmit the necessary current to the rotor. In a conventional machine the field winding has a time constant of approximately 2 - 10 seconds.

With this invention with an auxiliary winding it is possible to reduce the contribution of the fault current, generated by the magnetic rotating flux, faster than in conventional machines. This is due to that the time constant for a winding in the stator is lower than for a winding in the rotor and due to that there is easier to control the current in a winding in the stator than in a winding in the rotor.

The invention can for instance be realised, as shown in Fig. 12, by connecting the auxiliary winding (4) to a frequency converter (15) that can generate a controllable current in the auxiliary winding (4). If an internal fault occurs in the machine (1) the machine (1) is disconnected from the power network (7) with the breaker (3). At the same time the frequency converter (15) starts to generates a rotating magnetic flux with an opposite magnitude in the auxiliary winding (4). These two rotating magnetic fluxes will superpose to zero; the rotating magnetic flux will then be eliminated faster then in a conventional way.

In Fig. 12 the frequency converter (15) is controlled by the measurement equipment (19) via control signals (20). The measurement equipment (19) measures the rotor angle with the rotor angle measurement signal (24).

With this invention the fault current will be eliminated faster than with a conventional system.

Reduction of harmonics.

When calculating and designing three-phase alternating current machines, the aim is normally to achieve as symmetrical and sinusoidal quantities as possible. In order to obtain an economic yield from the electromagnetic circuit in common types current machines, harmonic electromotive forces are generated as harmonics to the fundamental electromotive force. These harmonic electromotive forces may under certain conditions cause harmonic

currents to flow in the current machine and in the power network.

It is well known that the chording of the stator winding may be chosen in order to eliminate one or more of the harmonics. It is also well known regarding current machines with salient poles that, in addition, the shape of the electromotive force of these machines may be influenced and improved by choosing the design of the rotor poles and, especially, the shape of the pole shoes in an appropriate way.

A total elimination of the third harmonic of the voltage by choosing an appropriate size for the winding step however means a considerable reduction, approximately 14 %, of the fundamental frequency voltage available for torque generation. Thus, this means only 86 % utilization of the possible rated power. In order to avoid this reduction, the winding step is used mainly for suppression of the fifth harmonic where by the reduction becomes only a few percent. Adaptation of the shape of the pole shoe is often used for a cost-effective reduction of the seventh harmonic voltage. Elimination or reduction of the harmful effects of the third-harmonic voltage/current must thus be performed by other methods.

Conventional generators are usually connected to the power network via a delta/wye-zero connected step-up transformer. The main purpose of this transformer is to increase the voltage from generator level, typically in the range 10 - 20 kV, to the voltage of the power network which can be several hundred kV. The delta winding of the transformer, which is connected to the generator, has the feature that it blocks third harmonic currents.

When a machine is directly connected to the power network this third harmonic voltage (depends on the grounding of the generator) results in a third harmonic current in the power network. To reduce this third harmonic current it is possible to chose a high impedance generator grounding, grounding with a third harmonic filter or isolated neutral.

When a direct grounding is required the third harmonic problem is not solved with the techniques described above.

With a machine according to the invention with an auxiliary winding in the stator it is possible to reduce or cancel the harmonics generated in the machine. This can be accomplished by injecting a current in the auxiliary winding which is controlled in such a way that it produces a magnetic flux in the machine that will superimpose on the generated harmonic magnetic flux produced by the machine such that the resulting harmonic magnetic flux is reduced or canceled. This will reduce or cancel the contribution of harmonics from the machine.

The invention can for instance be realized, as shown in Fig. 13, by connecting the auxiliary winding (4) to a frequency converter (15) that can generate a controllable magnetic flux in the machine. The frequency converter (15) is controlled in such a way that the auxiliary winding (4) generates a magnetic flux which superimpose on the generated harmonic magnetic flux produced by the machine such that the resulting harmonic magnetic flux is reduced or canceled. This will reduce or cancel the contribution of harmonics from the machine.

Compensating for external negative sequence currents.

For a conventional synchronous machine and for balanced system conditions, the air gap flux rotates in the same direction and in synchronism with the field winding on the rotor. During unbalanced system conditions, negative sequence current is produced. There are a number of sources of unbalanced three phase currents to a machine. The most common causes are system asymmetries (*e.g.*, untransposed transmission lines), unbalanced loads, unbalanced system faults, and open circuits (*e.g.*, broken conductor). The negative sequence

current component rotates in the opposite direction from the rotor. The flux produced by this current as seen by the rotor has a frequency of twice the synchronous speed as a result of the reverse rotation combined with the positive rotation of the rotor. The skin effect of the twice frequency rotor current causes it to be forced into the surface elements of the rotor. These rotor currents can cause dangerously high temperatures in a very short time. It is common practice to provide protection for the generator for external negative sequence currents. This protection consists of a time overcurrent relay which is responsive to negative sequence current and usually operates by tripping the generator breaker.

With a permanent magnet rotor with damper windings, negative sequence currents in the stator winding will induce currents of twice the frequency in the damper winding and possibly also in other parts of the rotor made of iron. If the synchronous machine is equipped with an auxiliary winding according to the invention, it is possible to run the machine although the machine is exposed to external negative sequence currents. This can be accomplished by injecting a negative sequence current in the auxiliary winding which produce a negative sequence air gap flux component such that the negative sequence air gap flux component due to the negative sequence current in the main winding is cancelled or reduced to the extent that dangerous rotor heating is avoided.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a functional block diagram of a synchronous machine excitation control system;

Fig. 2 is a schematic functional block diagram of a control system for a synchronous machine with permanent magnet rotor according to the invention;

Fig. 3 is a capability diagram illustrating characteristic features of a machine

according to the invention;

Fig. 4A is a schematic illustration of a machine according to the present invention;

Fig. 4B is a fragmentary illustration in perspective of a cable used in the machine according to the invention;

Figs. 5-18 are schematic block diagrams illustrating various control equipment in accordance with the present invention; and

Fig. 19 is an illustration of a conventional control system.

To explain the invention in more detail and in order to understand certain aspects of the advantages of the invention embodiments of the auxiliary winding(s) and to the auxiliary winding(s) connected equipment according to the invention, chosen as examples, will now be described in more detail with reference to Fig. 4 - Fig. 19 on the accompanying drawings on which:

Fig. 4A shows a schematic view of a sector of the stator (51) of a machine where an auxiliary winding (56) can be placed. The permanent magnet rotor is represented by (52), in this example a salient pole rotor, (55), (54) and (53) represent the main winding. In this embodiment the auxiliary winding (56) are placed in the back of the stator. Other placements of the auxiliary winding (56) is naturally possible.

Fig. 4B illustrates an exemplary cable (57) employed as a winding in the machine (1) of Fig. 4A. The cable (57) comprises a conductive core (58) formed of a plurality of conductive strands which may be transposed and which are generally insulated except for a few strands (59A) near the periphery, which are uninsulated. The cable (57) has a magnetically permeable, field-confining insulating cover (60) in accordance with the invention. The cover (60) comprises a first or inner layer (61) surrounding the conductive

core (58). In the exemplary embodiment the first cover (61) has semiconducting properties. Surrounding the inner layer there is provided a solid insulating layer (62) formed of an insulating material which is bonded along its interface with the inner layer (61). Surrounding the insulating layer (62) is an second or outer layer (63) which is formed of a material having semiconducting properties and which is bonded to the insulating layer (62) at the interface. The arrangement illustrated in Fig. 4B is as described in the above-identified applications and needs little further in the way of explanation except to state that the cable is capable of sustaining a high voltage and producing an equipotential surface which confines the electric field and yet allows the cable to be magnetically permeable and thus be an operative part of a magnetic circuit.

Fig. 5 shows a preferred embodiment of the invention where the machine (1) is connected to a power network (7) and the auxiliary winding (4) is connected to a passive, and if desirable, controllable R, L, C - circuit (8). This R, L, C - circuit (8) can comprise one or more passive element such as resistors, capacitors or inductors connected in series or parallel, delta or wye and if desirable to ground. This R, L, C - circuit (8) can also comprise breakers, thyristors of semiconductor power switches. The connection to ground can not be seen in the Figure, nor that the passive elements can be controllable.

With a circuit comprising a capacitor connected to the auxiliary winding (4) the machine (1) is able to produce extra reactive power and give an extra contribution of reactive power to the power network (7). If the circuit connected to the auxiliary winding (4) comprises an inductor the machine (1) is able to consume reactive power from the power network. If the circuit connected to the auxiliary winding (4) comprises a resistor the machine (1) is able to consume active power, this will generate a braking/damping torque to

the machine (1).

Fig. 6 shows another preferred embodiment of the invention where the machine (1) is connected to a power network (7) and the auxiliary winding (4) is connected to a four quadrant frequency converter. In the figure the frequency converter (9) is showed as an AC/DC converter (9) and a battery as an energy storage (10). The energy store (10) can also be a capacitor or another component that can store energy. The AC/DC converter (9) can be a four quadrant Pulse Width Modulated converter (PWM). Other types of converters are also possible.

With this invention it is possible to continuously and fast affect the interchange of active and reactive power between the AC/DC converter (9) and the auxiliary winding (4).

The AC/DC converter (9) can provide with both balanced and unbalanced three-phase quantities.

Fig. 7 shows another preferred embodiment of the invention, almost the same configuration as in Fig. 6 but with the addition of via a breaker (3) connected passive R, L, C - circuit (8).

With this preferred embodiment of the invention it is possible to use a switched passive R, L, C - circuit (8) to make slower discrete steps in the interchange of active and reactive power between the auxiliary winding (4) and the R, L, C - circuit (8) and use an AC/DC converter (9) and an energy store (10) to make the faster continuos interchange.

Fig. 8 shows another preferred embodiment of the invention similar to the invention shown in Fig. 6 but with the addition that the auxiliary winding (4) is connected to the auxiliary power network (12) via an AC/DC converter (9), an energy store (10) and a DC/AC converter (11). Both of the converters can be four quadrant converters, *e.g.,* PWM

converters.

With this preferred embodiment of the invention it is also possible to use the auxiliary winding (4) to feed the auxiliary power network (12) with power at rated voltage and frequency within prescribed tolerances via the AC/DC converter (9), the energy store (10) and the DC/AC converter (11).

Fig. 9 shows another preferred embodiment of the invention similar to the invention shown in Fig. 8 with the addition of via a breaker (3) connected passive R, L, C - circuit (8). Both of the converters can be four quadrant converters, *e.g.* PWM converters.

With this preferred embodiment of the invention a combination of the advantages shown in Fig. 7 and Fig. 8, already described, is achieved.

Fig. 10 shows another preferred embodiment of the invention similar to the invention shown in Fig. 9 with the difference that the auxiliary power bus bar (12) is connected to the power network (7) via a transformer (13).

With this preferred embodiment of the invention it is possible to continuously feed the energy storage (10) by the power network (7) via the transformer (13).

Fig. 11 shows another preferred embodiment of the invention similar to the invention shown in Fig. 8 with the addition of an extra auxiliary winding (14) and an extra AC/DC converter (27).

With this preferred embodiment of the invention the control equipment may be simpler due to that each auxiliary winding (4) and (14) can be dedicated to separate tasks.

Fig. 12 shows another preferred embodiment of the invention similar to the invention shown in Fig. 8 with the addition of a measurement equipment (19). (24) is a rotor angle measurement signal. Other control signals can also be measured.

With this preferred embodiment of the invention it is possible to use the auxiliary winding (4) to reduce the fault current in the case of an internal fault.

Fig. 13 shows another preferred embodiment of the invention similar to the invention shown in Fig. 8 with the addition of a transformer (13) and a measurement equipment (19). In this figure the measurement equipment (19) measures generated harmonics from the machine (1) via a transformer (13). Other control signals can also be measured. The frequency converter (15) is controlled by the measurement equipment (19) via control signals from the measurement equipment to the frequency converter (20).

With this preferred embodiment of the invention it is possible to use the auxiliary winding (4) to reduce the generated harmonics from the machine (1).

Fig. 14 shows another preferred embodiment of the invention where the machine (1) is connected to a power network (7) with a breaker (3) connected capacitor (6) and resistor (28) attached to the auxiliary winding (4).

With this preferred embodiment of the invention it is possible to use the auxiliary winding (4) and the capacitor (6) to produce or consume reactive power and thus contribute with extra capability of injecting reactive power from the power network (7).

Fig. 15 shows another preferred embodiment of the invention similar to the invention shown in Fig. 14 with the addition of a numbers of breakers (3) connected capacitors (6) and reactors (28).

With this preferred embodiment of the invention, similar to the invention described in Fig. 14, it is possible to use the auxiliary winding (4), the capacitors (6) and resistors (28) to produce or consume reactive power and thus contribute with extra capability of injecting or extracting reactive power from the power network (7). Due to the breakers (3) this

injection/extraction of reactive power can be made in discrete steps.

Fig. 16 shows another preferred embodiment of the where the auxiliary winding (4) is connected to a Static Var Capacitor (SVC) of the TSC/TCR type(21).

With this preferred embodiment of the invention it is possible to use the auxiliary winding (4) and the SVC (21) to produce or consume reactive power and thus contribute with extra capability of injecting or extracting reactive power from the power network (7). Due to the SVC (21) a change of this contribution of reactive power can be made faster than if breakers are used.

Fig. 17 shows another preferred embodiment of the invention where the auxiliary winding (4) is connected to a breaker (3) connected resistor (22).

With this preferred embodiment of the invention it is possible to use the auxiliary winding (4) and a resistor (22) to electrically brake the machine (1).

Fig. 18 shows another preferred embodiment of the invention where the auxiliary winding (4) is connected to a thyristor controlled (23) resistor (22).

With this preferred embodiment of the invention it is possible to use the auxiliary winding (4) with the thyristor controlled (23) resistor (22) to electrically brake the rotor speed.

Fig. 19 shows a block diagram representation of a conventional machine with conventional AVR (Automatic Voltage Regulator) and PSS (Power System Stabilizer).

The following is a listing of the components described hereinabove, with the accompanying reference numbers, and which should not be construed as limitation as to the invention.

1 - Machine

2 - Main winding

3 - Breaker

4 - Auxiliary winding

5 - Grounding equipment

6 - Capacitor

7 - Connection to a power network

8 - R, L, C - circuit

9 - AC/DC converter

10 - Energy store

11 - DC/AC converter

12 - Auxiliary bus bar

13 - Transformer

14 - Auxiliary winding 2

15 - Frequency converter

19 - Measurement equipment

20 - Control signals from the measurement equipment to the frequency converter

21 - Static Var Compensator of the TSC/TCR type

22 - Resistor

23 - Thyristor control unit

24 - Rotor angle measurement signal

25 - Control unit for the frequency converter

26 - Control signals from the control unit to the frequency converter

27 - AC/DC converter

28 - Reactor

51 - Stator according to the invention

52 - Permanent magnetic rotor

53 - Part of main winding

54 - Part of main winding

55 - Part of main winding

56 - Auxiliary winding

57 - Cable

58 - Core

59 - Strands

59A - Uninsulated strands

60 - Core

61 - First/Inner layer

62 - Insulating layer

63 - Second/Outer layer

While there has been provided what are considered to be exemplary embodiments of the invention, it will be apparent to those skilled in the art that various changes may be made therein without departing from the invention. It is intended in the appended claims to cover such changes and modifications as fall within the true spirit and scope of the invention.

I claim:

1. A rotating electric machine for high voltage for connecting to a power network comprising a stator, a rotor including at least one permanent magnet rotor, and at least two windings, wherein at least one of said windings comprises a main winding for connection to the power network for at least one of producing or consuming power and at least one of said windings comprises an auxiliary winding for controlling the magnetic flux in the machine, and at least one of said windings comprises a cable including at least one current-carrying conductor and a magnetically permeable, electric field confining insulating cover surrounding the conductor, said cable forming at least one uninterrupted turn in the corresponding winding of the machine.

2. The rotating electric machine of claim 1, wherein the cable comprises at least one semiconducting layer surrounding the conductor.

3. A rotating electric machine according to claim 2, wherein said at least one semiconducting layer has substantially the same coefficient of thermal expansion as the insulating layer.

4. The rotating electric machine according to claim 1, wherein said cover comprises an insulating layer surrounding the current-carrying conductor and an outer layer surrounding the insulating layer having semiconducting properties for producing an equipotential field confining surface.

5. A rotating electric machine according to claim 4, wherein the cable further comprises an inner layer between the current-carrying conductor and the insulating layer having semiconducting properties.

6. A rotating electric machine according to claim 4, wherein the outer layer forms an

equipotential surface surrounding the conductor.

7. A rotating electric machine according to claim 5, wherein the inner and outer layers have corresponding contact surfaces and are secured to the adjacent insulating layer along the length of each corresponding contact surface.

8. A rotating electric machine according to claim 4, wherein the outer semiconducting layer is connected to a selected potential.

9. A rotating electric machine according to claim 8, wherein the selected potential is earth potential.

10. A rotating electric machine according to claim 4, wherein each winding is connectable to a separate potential.

11. A rotating electric machine according to claim 4, wherein the cable is flexible.

12. A rotating electric machine according to claim 5, wherein the current-carrying conductor comprises a first plurality of insulated strands and at least one uninsulated strand in electrical contact with the inner layer.

13. A rotating electric machine according to claim 1, wherein the cover has conductivity sufficient to establish an equipotential surface around the conductor.

14. A rotating electric machine according to claim 1, further comprising means coupled to the auxiliary winding for selectively adding and removing power from the machine.

15. The rotating electric machine of claim 1, wherein the power is at least one of active power and reactive power.

16. The rotating electric machine of claim 1, further comprising control means coupled to at least the auxiliary winding for controlling at least one of the phase, amplitude

and frequency of the magnetic flux in the machine.

17. A rotating electric machine according to claim 1, further including at least one inverter/converter and a DC energy storage means coupled to the auxiliary winding.

18. A rotating electric machine according to claim 1, further including a transformer coupled between an output of the main winding and the auxiliary winding.

19. A rotating electric machine according to claim 1, including an RLC circuit coupled to the auxiliary winding.

20. A rotating electric machine according to claim 19, including at least one of three-phase resistors, inductances and capacitors in the RLC-circuit being connected in Y or delta.

21. A rotating electric machine according to claim 19, wherein the RLC circuit includes switch means for selectively switching the RLC for controlling the magnetic flux in the machine.

22. A rotating electric machine according to claim 21, wherein the switch means comprises at least one of a breaker and a semiconductor power switch.

23. A rotating electric machine according to claim 1, further including a second auxiliary winding.

24. A rotating electric machine according to claim 23, further including at least one inverter for each auxiliary winding.

25. A rotating electric machine according to claim 20, wherein the reactive means comprises at least one capacitor and a corresponding switch in shunt with the auxiliary winding.

26. A rotating electric machine according to claim 1, further comprising a resistor switchably connected in at least one of delta and Y with the auxiliary winding.

27. A rotating electric machine according to claim 26, wherein the switch means comprises at least one of a breaker, a semiconductior switch and a thyristor.

28. A rotating electric machine according to claim 1, further comprising sensor means coupled to the main winding for producing an output and means coupled to the auxiliary winding responsive to the output and for injecting or extracting power in the auxiliary wing.

29. A rotating electric machine according to claim 1, wherein the auxiliary winding is located in at least one of the rotor and stator and further comprising means controlling at least one of phase, amplitude and frequency of the flux of the machine.

30. A rotating electric machine according to claim 1, wherein the main winding and the auxiliary winding are located in the stator.

31. A rotating electric machine according to claim 1, wherein at least one stator winding is a three-phase winding.

32. A rotating electric machine according to claim 1, including multiple phase windings and wherein each phase is individually controllable for compensating for unbalanced loading of the main winding.

33. A rotating electric machine according to claim 1, wherein the rotor is substantially free of winding loss.

34. The rotating electric machine of claim 33, wherein at least one auxiliary winding is located in the permanent magnetic rotor, further comprising means for controlling the magnetic flux in the machine by controlling the current in the auxiliary winding.

35. A rotating electric machine according to claim 37, wherein the means for controlling flux in the machine is coupled before the auxiliary winding and the field winding.

36. A rotating electric machine according to claim 1, wherein the auxiliary winding

also produces auxiliary power.

37. A rotating electric machine for high voltage comprising a stator, a permanent magnet rotor, and at least two windings, wherein at least one of said windings comprises a main winding for producing or consuming power and at least one auxiliary winding for controlling the magnetic flux in the machine, and at least one of said windings comprises a cable including at least one current-carrying conductor and a magnetically permeable, electric field confining insulating cover surrounding the conductor, said cable forming at least one uninterrupted turn in the corresponding winding of the machine, said rotor being substantially free of field winding loss.

38. A rotating electric machine according to claim 17, wherein the inverter/converter is a four quadrant converter/inverter.

39. A rotating electric machine according to claim 28, wherein the sensor means senses the main winding terminal voltage and the means coupled to the auxiliary winding are such that reactive power can be injected or extracted from the auxiliary winding such that the main winding terminal voltage is kept at desired magnitude.

40. A rotating electric machine according to claim 28, wherein the sensor means senses power oscillations in the power network and the means coupled to the auxiliary winding are such that power can be injected or extracted from the auxiliary winding such that the oscillations in the air gap flux are reduced or eliminated.

41. A rotating electric machine according to claim 28, wherein the sensor means senses an internal fault in the machine and the means coupled to the auxiliary winding are such that reduction of the magnetic flux in the machine in order to reduce the fault current can be accomplished if appropriate.

42. A rotating electric machine according to claim 28, wherein the sensor means senses the harmonic content of the magnetic flux in the machine and the means coupled to the auxiliary winding are such that magnetic flux components can be produced via the auxiliary winding such that the resulting magnetic flux has a reduced or eliminated harmonic content.

43. A rotating electric machine according to claim 28, wherein the sensor means senses a disturbance in the power network and the means coupled to the auxiliary winding are such that dynamic braking to reduce rotor acceleration can be accomplished if appropriate.

44. A rotating electric machine according to claim 28, wherein the sensor means senses unbalanced phase currents in the main winding and the means coupled to the auxiliary winding are such that unbalanced currents can be injected in the auxiliary winding such that substantially only positive sequence magnetic flux remains in the machine.

45. A rotating electric machine according to claim 1, wherein the main winding comprises said cable.

FIG. 1

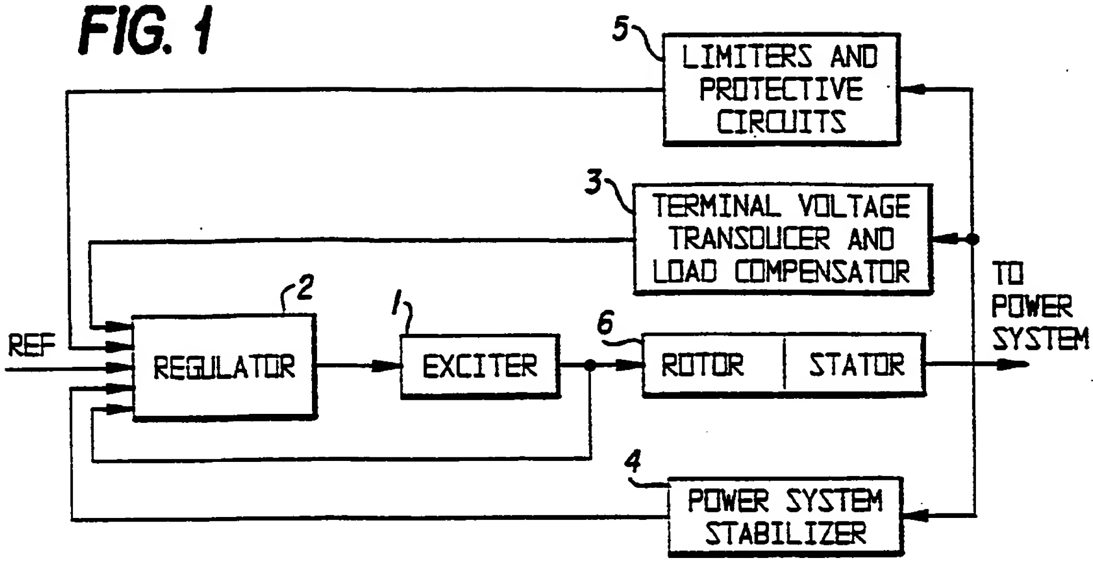
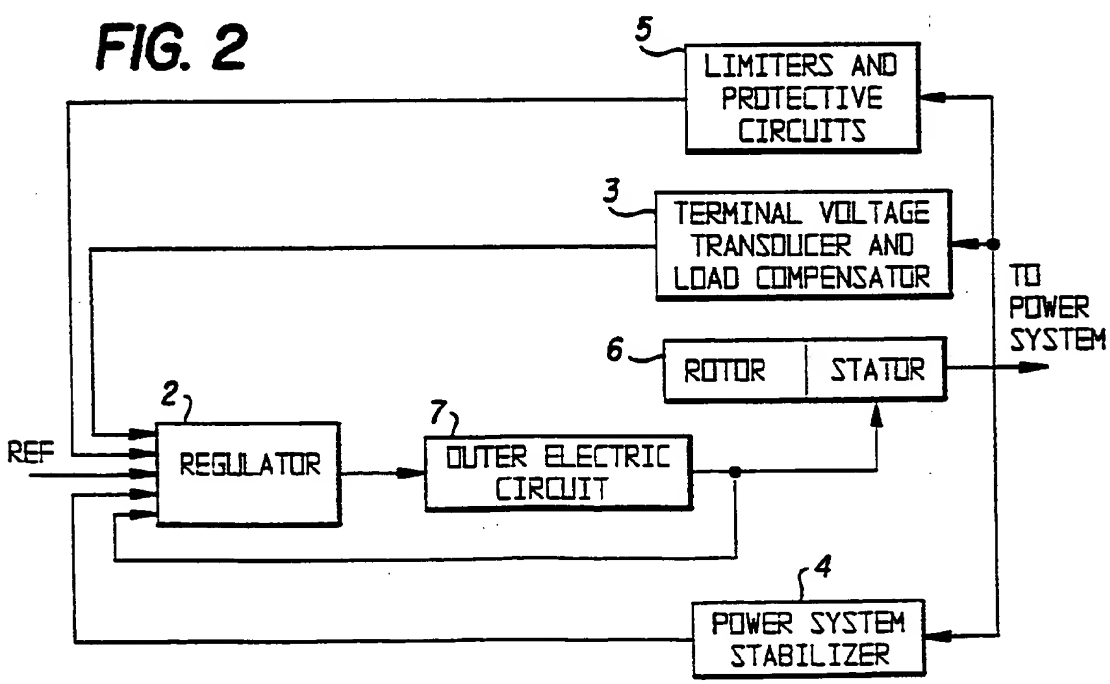

5
LIMITERS AND PROTECTIVE CIRCUITS
3
TERMINAL VOLTAGE TRANSDUCER AND LOAD COMPENSATOR
2
1
6
REF
REGULATOR
EXCITER
ROTOR
STATOR
TO POWER SYSTEM
4
POWER SYSTEM STABILIZER

FIG. 2


5
LIMITERS AND PROTECTIVE CIRCUITS
3
TERMINAL VOLTAGE TRANSDUCER AND LOAD COMPENSATOR
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ROTOR
STATOR
TO POWER SYSTEM
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7
REF
REGULATOR
OUTER ELECTRIC CIRCUIT
4
POWER SYSTEM STABILIZER

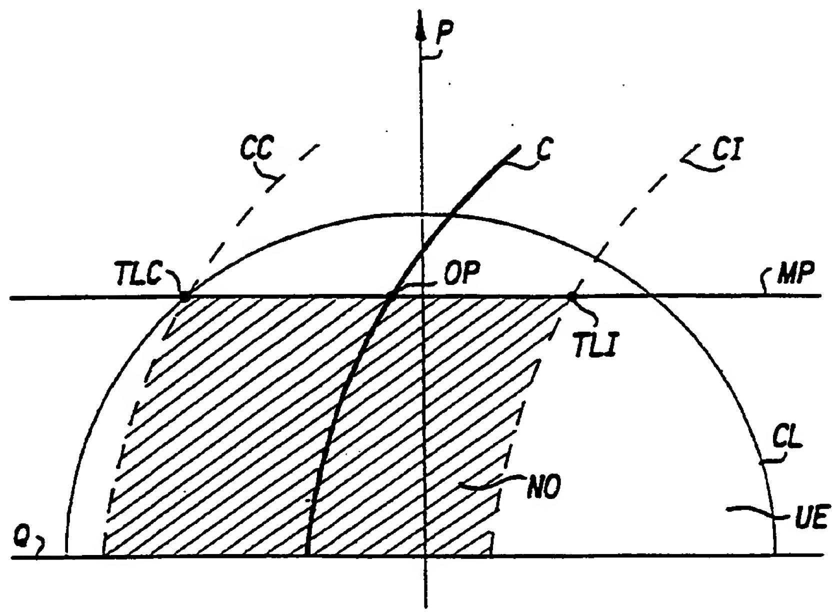


FIG. 3

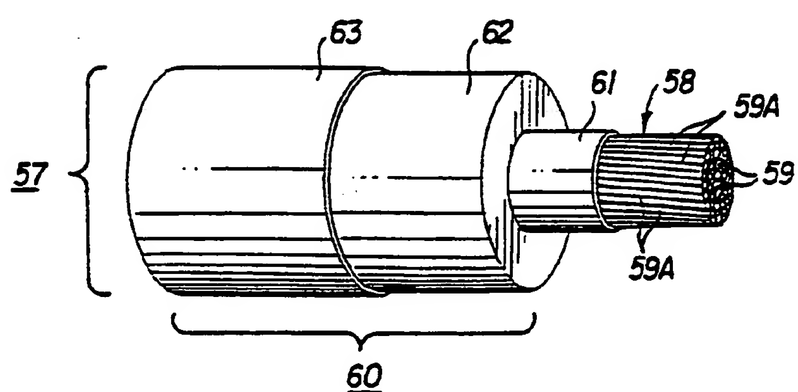


FIG. 4B

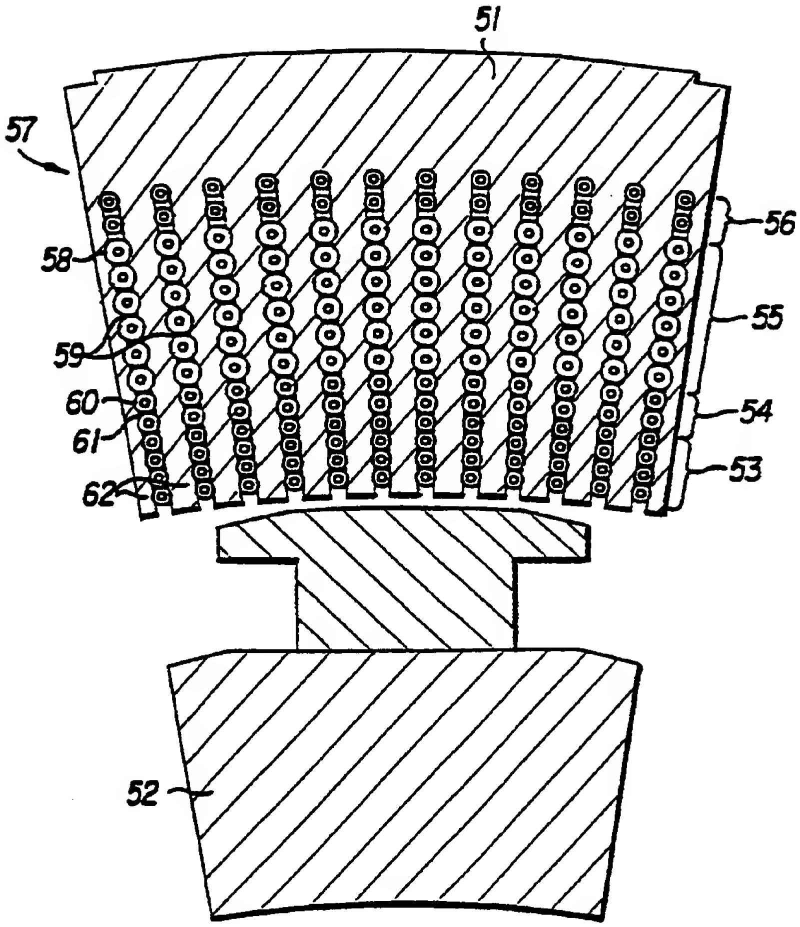


FIG. 4A

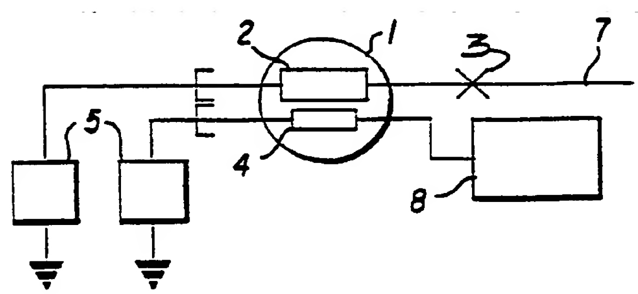


FIG. 5

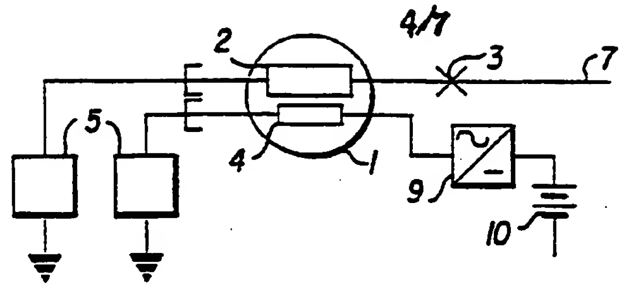


FIG. 6

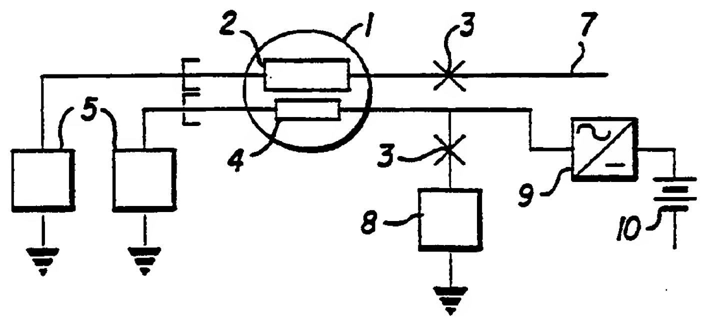


FIG. 7

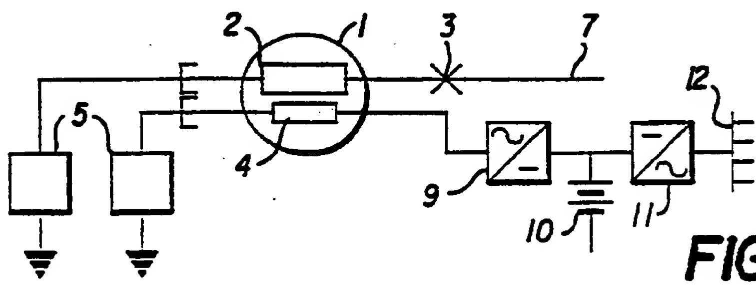


FIG. 8

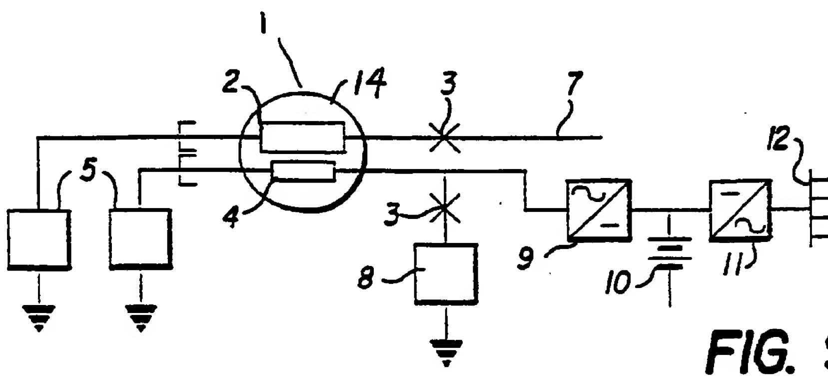


FIG. 9

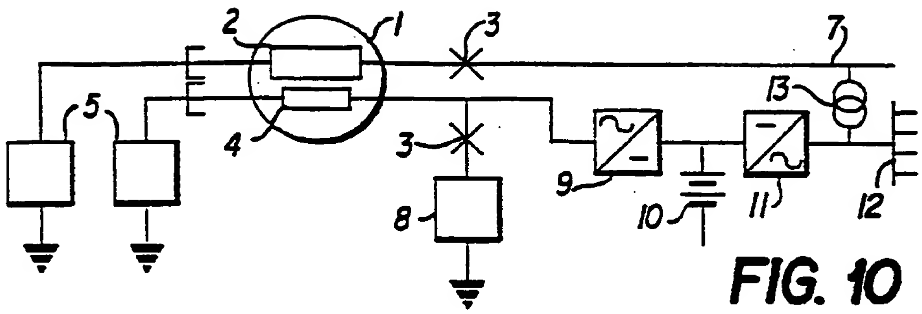


FIG. 10

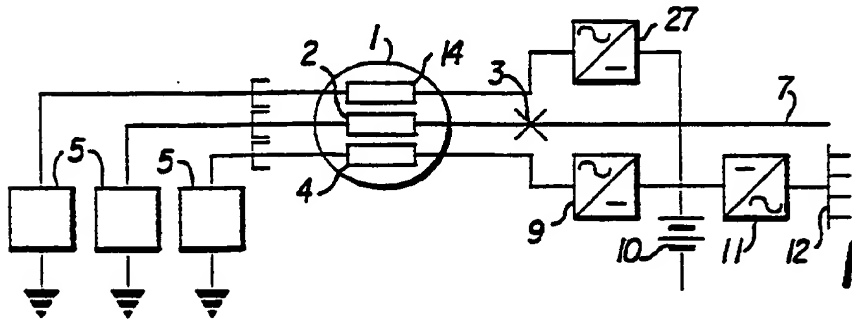


FIG. 11

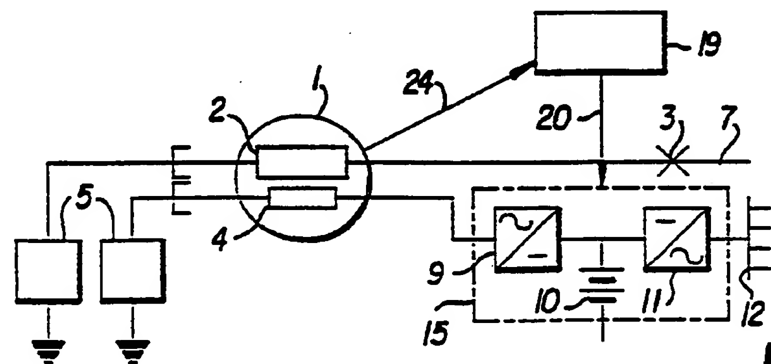


FIG. 12

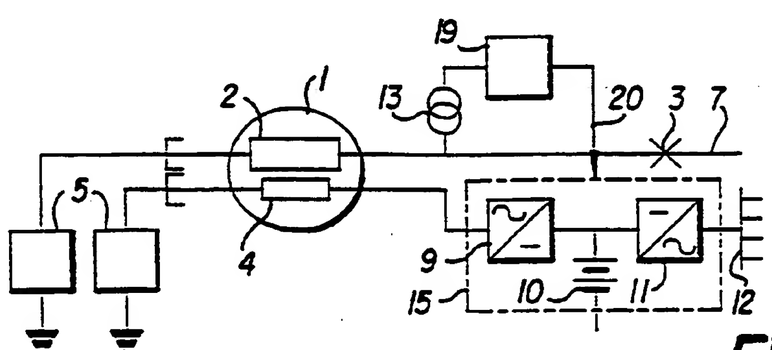


FIG. 13

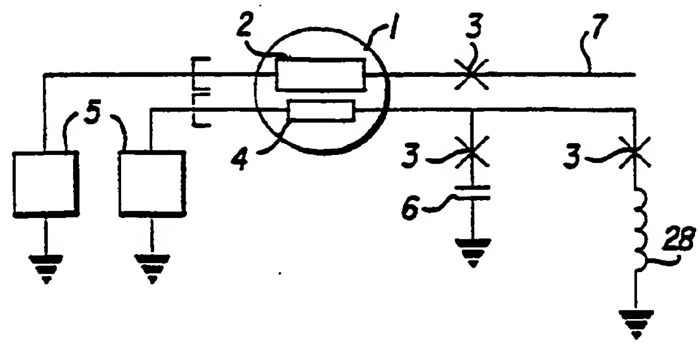


FIG. 14

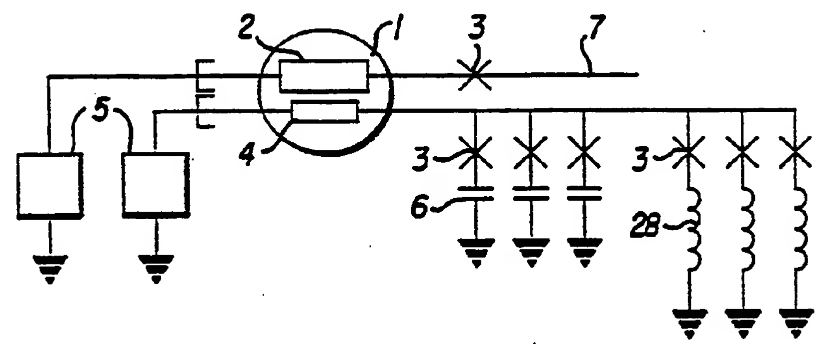


FIG. 15

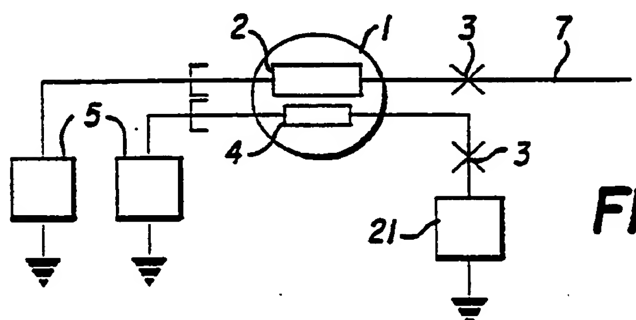


FIG. 16

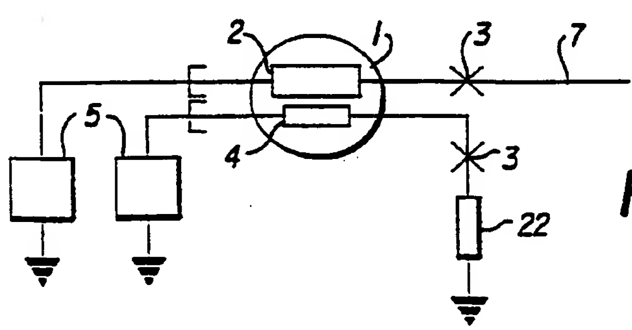
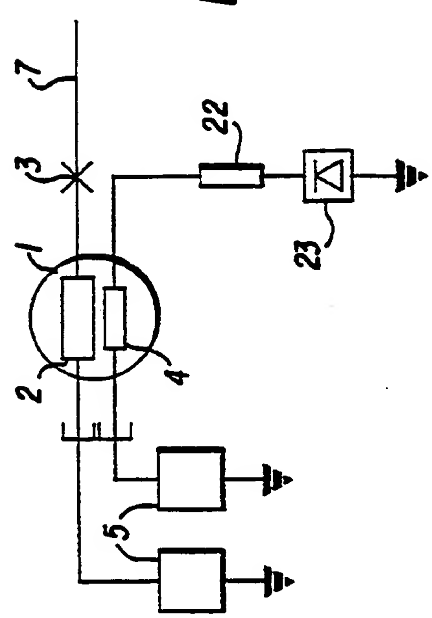


FIG. 17


1
2
3
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22
23

FIG. 18

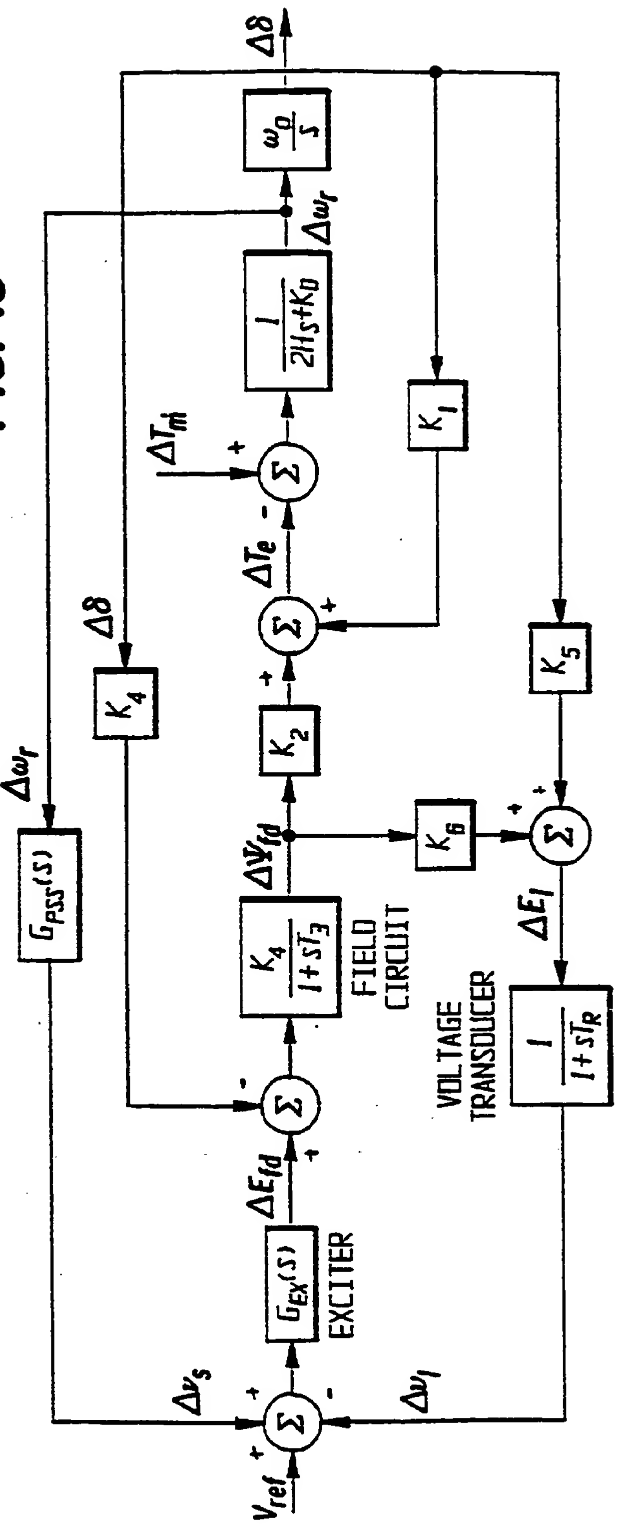
Δδ
ω0 / s
Δωr
1 / 2Hs+KD
ΔTm
ΔTe
K1
Δδ
K4
K2
K5
Δωr
GPSS(S)
ΔΨfd
K6
ΔE1
K4 / 1+sT3
FIELD CIRCUIT
VOLTAGE TRANSDUCER
1 / 1+sTR
ΔEfd
GEX(S)
EXCITER
Δvs
Δv1
Vref

FIG. 19